Summer melt regulates winter glacier flow speeds throughout Alaska

Evan W. Burgess,[1,2] Christopher F. Larsen,[1] and Richard R. Forster[3]

Received 3 October 2013; revised 20 November 2013; accepted 21 November 2013; published 10 December 2013.

[1] Predicting how climate change will affect glacier and ice sheet flow speeds remains a large hurdle toward accurate sea level rise forecasting. Increases in surface melt rates are known to accelerate glacier flow in summer, whereas in winter, flow speeds are believed to be relatively invariant. Here we show that wintertime flow speeds on nearly all major glaciers throughout Alaska are not only variable but are inversely related to melt from preceding summers. For each additional meter of summertime melt, we observe an 11% decrease in wintertime velocity on glaciers of all sizes, geometries, climates, and bed types. This dynamic occurs because interannual differences in summertime melt affect how much water is retained in the subglacial system during winter. The ubiquity of the dynamic indicates it occurs globally on glaciers and ice sheets not frozen to their beds and thus constitutes a new mechanism affecting sea level rise projections. **Citation:** Burgess, E. W., C. F. Larsen, and R. R. Forster (2013), Summer melt regulates winter glacier flow speeds throughout Alaska, *Geophys. Res. Lett.*, *40*, 6160–6164, doi:10.1002/2013GL058228.

1. Introduction

[2] While marine-terminating glaciers will undoubtedly contribute the majority of flow-related mass loss in the coming century, ice sheets and mountain glaciers are also broadly sensitive to changes in flow speed that occur due to transformations in subglacial hydrologic drainage networks [*Parizek and Alley*, 2004]. Temporal and spatial variations in the volume and pressure of water draining underneath a glacier strongly influence flow speed [*Iken and Bindschadler*, 1986; *Iken and Truffer*, 1997; *Bartholomaus et al.*, 2008] and may influence mass balance [*Parizek and Alley*, 2004; *Shannon et al.*, 2013]. Summertime meltwater production will overpressurize subglacial drainage systems and lead to increased basal motion in spring and summer [*Iken and Truffer*, 1997; *Bartholomaus et al.*, 2008] and decreased basal motion in fall [*Sundal et al.*, 2011]. The impact these variations in basal motion have on mass balance has been modeled [*Parizek and Alley*, 2004; *Shannon et al.*, 2013] using parameterizations that scale summer and fall velocities against what is assumed to be invariant flow in winter. Such parameterizations suggest Greenland ice sheet mass loss will increase by only by 5% if spring through fall variations in velocity are considered [*Shannon et al.*, 2013]. But assuming an invariant wintertime speed would be inappropriate if wintertime velocity is variable and dependent on summer melt.

[3] Wintertime flow speeds are commonly assumed to represent a consistent "background velocity." But over the summer melt season, increased water input channelizes the subglacial drainage system; this increases drainage efficiency, lowers basal water pressures, and eventually draws water away from the glacier bed [*Iken and Truffer*, 1997; *Schoof*, 2010; *Sundal et al.*, 2011]. The cessation of water input in fall allows the subglacial drainage system to close, which traps water in cavities and consequently separates the glacier from the bed to some degree throughout winter [*Iken and Truffer*, 1997]. The volume of trapped water has generally been assumed to be dependent on unchanging bed geometry [*Walder and Hallet*, 1979; *Kamb*, 1987; *Werder et al.*, 2013] and thus seasonally invariant. But numerical models indicate variations in summertime melt affect the final development stage of channels [*Schoof*, 2010] and hence may affect the ability of those channels to evacuate subglacial water before it gets trapped by the rapidly closing drainage network in fall [*Truffer et al.*, 2005]. If so, consequent variations in the amount of basal water would persist through winter and lead to interannual variations in winter flow speed inversely related to summertime melt [*Iken and Truffer*, 1997; *Truffer et al.*, 2005].

[4] Isolated observations have indicated such a dynamic occurs on Black Rapids Glacier, Alaska and on Leverett Glacier in west Greenland [*Truffer et al.*, 2005; *Sole et al.*, 2013]. But since the volume of water trapped at the glacier bed in winter is likely dependent on bed topography [*Walder and Hallet*, 1979; *Kamb*, 1987; *Werder et al.*, 2013], these studies have been unable to ascertain whether this mechanism is likely to occur elsewhere. Consequently, we have yet to determine if this mechanism is relevant for global sea level rise projections. Here we provide the first widespread evidence that wintertime glacier speeds are interannually variable over large regions—on all types of glaciers—and are inversely related to summer melt rates due to changes in the seasonal evolution of subglacial drainage systems.

2. Methods

[5] We examine wintertime velocities on 160 independent glacier systems throughout the Alaska region [*Burgess et al.*, 2013] from 2006 to 2011 and relate these velocities to summertime positive degree days (PDDs) for each preceding summer. Our sample includes the full spectrum of glacier sizes, geometries, terminus types, and climates, varying from 7 km to 160 km in length, maritime through continental climates, and flow speeds [*Burgess et al.*, 2013] from 0.04 to 5 m d^{-1}. Thirty four tidewater glaciers, 35 lacustrine, and 37 surge-type

Additional supporting information may be found in the online version of this article.

[1]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2]Alaska Science Center, United States Geological Survey, Anchorage, Alaska, USA.
[3]Department of Geography, University of Utah, Salt Lake City, Utah, USA.

Corresponding author: E. W. Burgess, Geophysical Institute, University of Alaska Fairbanks, AK 99775, USA. (evanburgess@gi.alaska.edu)

0094-8276/13/10.1002/2013GL058228

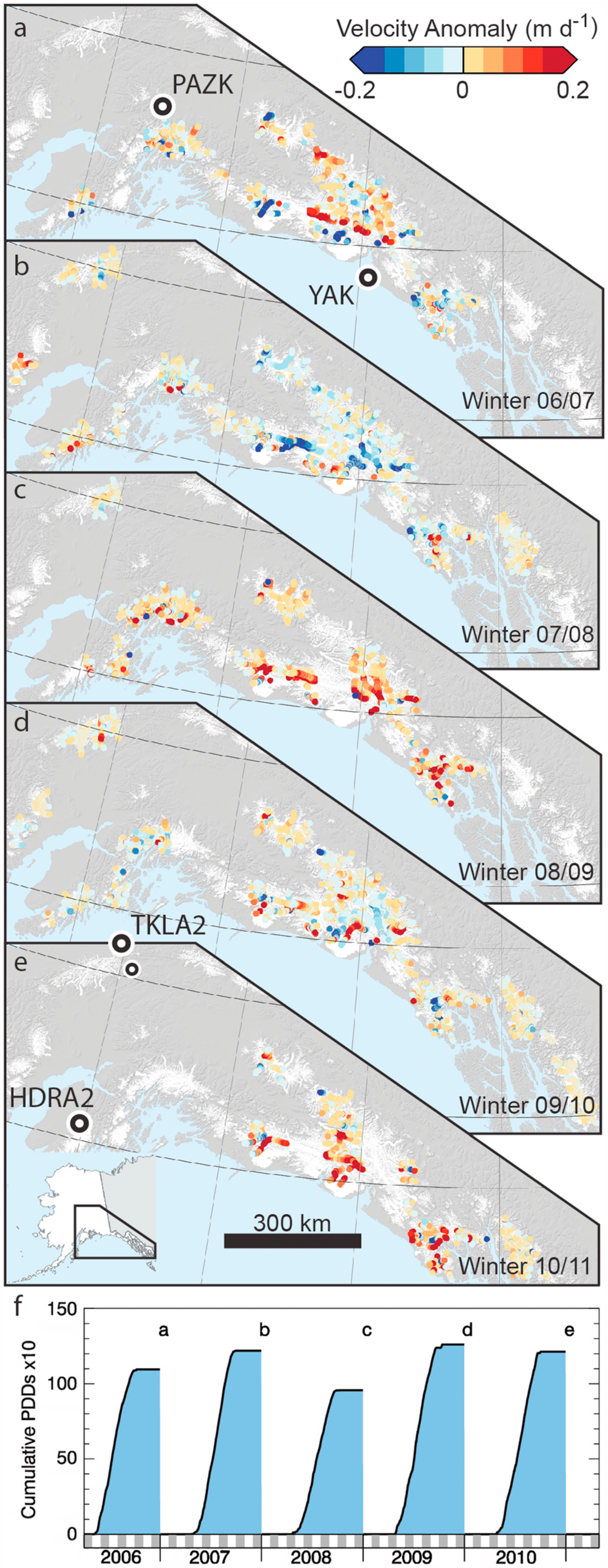

Figure 1. (a–e) Time series of December–March mean velocity anomalies in m d^{-1} along longitudinal profiles. Areas without data represent a lack of PALSAR data availability. Bullseyes locate meteorological stations discussed. (f) Time series of observed cumulative positive degree days at PAZK station (location in Figure 1a).

glaciers (glaciers that undergo a quasiperiodic state of accelerated flow) [*Harrison and Post*, 2003] are included in this sample as well as 72 land-terminating, non-surge-type glaciers.

2.1. Velocity Processing

[6] We derive glacier velocities using Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar (ALOS PALSAR) Fine Beam data (obtained from the Alaska Satellite Facility, www.asf.alaska.edu) and offset tracking methods described in *Burgess et al.* [2013]. All 46 day image pairs are processed for the entire Alaska region including the Coast Range, Glacier Bay, Fairweather, Wrangell-St. Elias, Alaska, Tordrillo, Chugach, and Kenai Mountains. This includes 550 image pairs covering 47,880 km^2 of glacier ice from 2006 to 2011. Only winters yielded usable data because melt in summer causes decorrelation [*Burgess et al.*, 2013]. We then extract velocity along 160 manually digitized glacier profiles (Figure 1). For each profile, we are able to obtain between ~4 and 30 (12 on average) observations of velocity at different times but not necessarily at discrete times due to overlapping acquisitions. Velocity uncertainties (determined using methods described in *Burgess et al.* [2013]) at any one location are ~1–4 cm d^{-1} (Figure S1a in the supporting information). Isolated larger errors occur due to mismatched correlation peaks but are removed through filtering [*Burgess et al.*, 2013]. Since this study examines velocity averaged along entire glacier profiles (including many individual offset estimates), our uncertainties lie closer to the image wide offset bias of around ~0.1–0.2 cm d^{-1} (Figure S1b). In effort to make all glaciers comparable, we convert absolute velocity along each profile to velocity anomalies, which requires a mean velocity profile. The short lifespan of ALOS data allows only a 5 year mean. While this may be too short to be considered a long-term mean, this mean still enables normalization of velocity change for each glacier and thus is effective at highlighting interannual variability. Velocity anomalies are derived by dividing each velocity profile by the mean profile; this normalizes anomalies for large/fast and small/slow moving glaciers.

[7] Examining interannual change in velocity requires that we avoid any aliasing from seasonal wintertime acceleration. From December through March, median rates of seasonal acceleration were ~1 mm d^{-2} and 0.5 mm d^{-2} in January. For our regressions and tests of significance, we only consider velocity observations with a midpoint date in January, requiring at least 50% overlap in dates from year to year at a time when seasonal acceleration is below detectable limits. Figure 1 includes data from December to March for better spatial coverage, but values are similar to maps derived from only January data. For almost all glaciers, wintertime seasonal variability is usually small compared to the interannual variability.

2.2. Positive Degree Day Model

[8] We derive a relative measure of total summertime meltwater input to glacier beds using PDDs. PDD models are a simple and effective method to estimate the surface ablation [*Ohmura*, 2001; *Hock*, 2003] that dominates water input to the bed [*Motyka et al.*, 2003]. While energy balance models could offer a more complete melt model, necessary inputs such as albedo and snow accumulation are unknown and highly variable. In coastal areas in Alaska, liquid precipitation does contribute to water input but can only be accounted for

qualitatively due to a lack of credible data or models. But melt rates in these areas are still higher than precipitation rates [*Pelto et al.*, 2008], and these areas are relatively few in number, thus PDDs should still provide a robust proxy for the variability of water input to the bed from year to year.

[9] Meteorological station data are extremely sparse in Alaska, and existing stations are subject to frequent malfunctions and local drainage effects. Consequently, we derive temperature using ERA-Interim data [*Uppala et al.*, 2005] downscaled to a 1 km grid and validated against station data where possible. ERA-Interim air temperature and geopotential height data are retrieved from 2006 to 2011 at pressure levels from 500 to 1000 mbar. ERA-Interim includes an estimate of air temperature to 1000 mbar, even when the model terrain is above this level. Temperatures below the model terrain generally increase along an environmental lapse rate of ~6.5°C km^{-1}. Thus, these data can be reasonably used to derive temperature for terrain that is below the coarsely resolved ERA model terrain. All pressure levels are bilinearly interpolated onto a 1 km grid to match a 1 km resolution digital elevation model (DEM) obtained from downsampling the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map 2.0[25]. Surface air temperature is then extracted at each pixel using elevations from the DEM and the interpolated temperature and geopotential height fields. A cumulative PDD estimate is then calculated for each 1 km pixel for the summers of 2006 to 2010. Finally, the mean PDD value along each glacier profile is used as a seasonal meltwater proxy.

[10] We validate the gridded temperature and PDD data sets by comparing them to measured air temperature at five meteorological stations (4 in Figure 1, another station is off map to west) scattered throughout the study region [*Horel et al.*, 2002]. Example comparisons with two stations of varying climates HRDA2 and TKLA2 are shown as Figures S2 and S3. HRDA2 is positioned in a maritime location on the Harding Icefield at an elevation of 1311 m. It is the only station immediately adjacent to large glaciers. At HRDA2, there is seasonal variability in model bias but nonetheless, very well replicated PDDs. TKLA2 is at a continental position. The downscaling biases are seasonally higher in winter due to cold air pooling. However, summertime temperatures are well simulated, and our PDD estimates conform to observed PDDs. At all five sites, we find our gridded PDD data set has a root-mean-squared error of 4.9%, thus does a reliable job of estimating PDDs throughout our study area.

2.3. Surface Velocity Model

[11] In effort to assign a mechanism to observed relationships between summertime melt and wintertime velocity, we model the expected velocity response to variations in driving stress caused by interannual differences in summertime melt. We employ a simplified model by invoking the shallow ice approximation and a Weertman sliding law, assuming all driving stress is balanced by bed parallel shear stress [*Cuffey and Paterson*, 2010],

$$u_s = u_b + \frac{2A}{n+1}\tau_b^n H \qquad u_b = \left[\frac{\tau_b^{0.5}}{R}\right]^{n+1}. \tag{1}$$

[12] Here, u_s and u_b are the surface and basal sliding velocities, respectively, H is the ice thickness, n and A are the creep exponent and flow parameter, R is a surface roughness parameter, and τ_b is the basal shear stress (here assumed to equal the driving stress). Granted, in Alaska, lateral shear is a key component to force balance [*O'Neel et al.*, 2005], but inclusion of a shape factor (that accounts for lateral stress gradients) reduces glacier flow sensitivity to driving stress thus exclusion of this term provides the largest possible response.

[13] We examine glacier thicknesses to 1000 m and slopes between 0.4° and 2.2° and roughness parameters from 0.05 to 0.4. We derive $\left(\frac{du_s}{dH}\right)u_s^{-1}$, which represents the proportional change in velocity per meter change in H; this function will be comparable to our observations.

3. Results

[14] We find that wintertime velocities are relatively stable each winter from December through March. But interannually, velocities are variable and show broad synchronicity throughout Alaska. Figure 1 shows wintertime velocity anomalies (relative to a 5 year mean) for hydrologic years of 2007–2011 and a time series of cumulative PDDs from each summer in central Alaska. There are only three glaciers that were known to be in surge phase during the observation period (Bering, south branch of Lowell, and Ottawa).

[15] The summer of 2007 had above average PDDs during the study period, and the following winter of 2007/2008 had anomalously slow flow velocities on all types of glaciers statewide (land/lake/tidewater, surge/not surge). Positive velocity anomalies did exist this winter but were almost entirely confined to low-elevation coastal locations. One such location, on Bering Glacier, likely represents an initial acceleration related to the onset of the Bering surge [*Burgess et al.*, 2012]. The following summer of 2008 was an extremely cold summer [*Horel et al.*, 2002], and in the following winter of 2008/2009, velocities were anomalously fast statewide—again on all types of glaciers. At this same time, Lowell Glacier began to surge and the first phase of the Bering surge was reaching peak speeds [*Burgess et al.*, 2012]. Over the 5 year observation interval, we observe no trend in velocity but rather a negative correlation with PDDs from previous summers. The surges of Bering and Lowell not only occur in synchrony but also occur in synchrony with fast wintertime velocity anomalies throughout Alaska.

[16] We find that the negative correlation between summertime PDDs and January-only velocities (avoiding any possible intraseasonal variation) is highly statistically significant ($p < 0.0001$), with a slope equivalent to an 11% reduction in flow speed per additional meter of summertime melt (Figure 2a, Table S1). This response applies to nearly all major glacier systems in Alaska. If the data are divided into tidewater, lake, and land-terminating glacier types, the relationships remain significant to $p < 0.0003$ (Figure 2b). We are unable to confirm if this relationship applies near calving fronts, due to scarce data. Surging glaciers show a less significant relationship due to their expected [*Harrison and Post*, 2003] highly variable behavior (Figure S4). But for all of these groups, the magnitude of the response remains remarkably consistent (Table S1). *Sole et al.* [2013] found qualitatively similar inverse relationships on Leverett Glacier, Greenland, but since they considered late summer PDDs normalized at each location, their observations are not directly comparable to ours.

[17] The surface velocity model confirms that this response is too large to be associated only with variations in driving

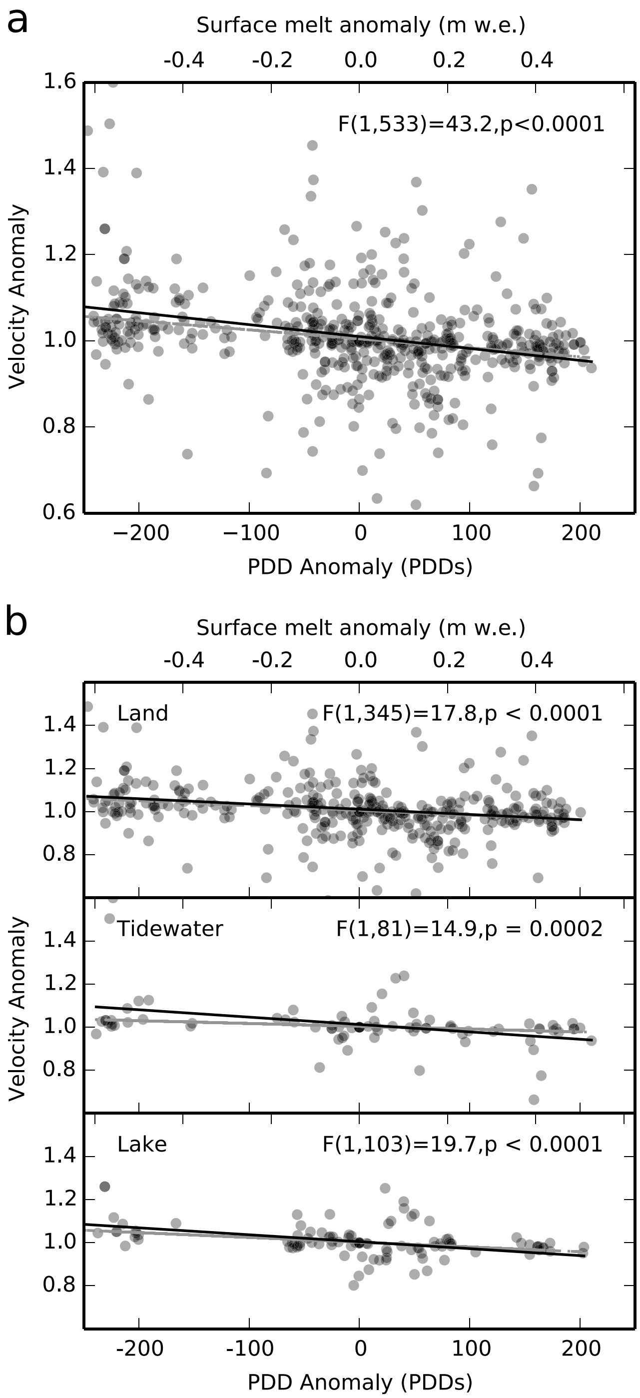

Figure 2. Velocity response to PDD anomalies. Least squares (black line) and Huber's robust linear model [*Huber and Ronchetti*, 2009] (grey line) of glacier wide mean velocity anomalies versus PDD anomalies for 2006–2011 (dots have transparency to see point density). Here, only January velocity data are used to avoid aliases intraseasonal velocity changes. Statistics apply to least squares model. Surface melt anomaly scale assumes a typical degree day factor for snow of 0.0025 [*Arendt et al.*, 2009]. (a) All data. (b) Data separated by terminus type.

stress (even when model parameters are stretched beyond reasonable values) and therefore must be due to hydrology (Figure S5d). Examination of the full parameter space of the model reveals that no realistic solution can achieve the velocity response observed.

4. Discussion

[18] Model results and additional observations confirm that the observed wintertime velocity variability must represent changes to bed hydrology. While summertime melt may decrease the driving stress and consequently slow velocities, our model suggests this response is far too small to account for the observations. Also, we observe no downward trend in velocity despite a statewide negative trend in total mass over our study period [*Arendt et al.*, 2013].

[19] Another observation that supports a hydrologic mechanism is at low elevations, along the gulf coast of Alaska; velocity anomalies in 2006/2007 and 2007/2008 are of opposite sign than the rest of the state (more negative/positive, respectively). This pattern cannot be explained by melt anomalies at these places and times, but in these coastal areas, rainfall rates may be sufficiently high to modulate water inputs to the bed. Unfortunately, we cannot include liquid precipitation in our regressions, as spatially variable precipitation data sets are unacceptably poor. Nonetheless, meteorological station data from Yakutat [*Horel et al.*, 2002] show that precipitation along the south coast can explain the coastal velocity anomalies that are unexplained by PDDs. During the summers of 2006 and 2007, liquid precipitation was anomalously high/low (Figure S5). The ensuing winters had anomalously slow/fast velocities, which would be expected under the hydrologic mechanism proposed.

[20] A second important observation supportive of a hydrological mechanism is that the surges on Bering Glacier and Lowell Glacier initiate in synchrony with high winter velocities statewide—suggesting a common mechanism. Glacier surges typically trigger in winter because of extensive bed separation from water-filled cavities [*Kamb*, 1987]. Thus, a cold summer would induce subglacial hydrologic conditions ideal for fast winter flow statewide and would also present ideal conditions for surge triggering. In a warming climate, this also implies surging could become less frequent.

[21] These observations all confirm interannual variations in meltwater production must affect the volume of water trapped subglacially in winter and hence inversely affect winter sliding velocity.

5. Conclusions

[22] The ubiquity of the observed wintertime flow response to summertime PDDs over a great variety of glacier geometries and types—including surging and tidewater glaciers—indicates that interannual variations in wintertime basal motion persist despite differences in glacier geometry, climate, and bed conditions. Given these observations, we see no physical reason why the hydrologic mechanism proposed would act differently in other mountain regions or anywhere in Greenland where ice is not frozen to the bed. The uniformity of the observed response means this process can be easily parameterized in flow models. Furthermore, we find that parameterizations that scale melt period speedup against wintertime velocity [*Shannon et al.*, 2013] are inappropriate as they assume interannually invariant winter flow speed. Our results also suggest that spatially variable parameters (such as small-scale bed topography) may play less of a role than physics included in existing models [*Schoof*, 2010; *Hewitt et al.*, 2012; *Schoof et al.*, 2012; *Werder et al.*, 2013]. As such, subglacial hydrologic modeling represents a key knowledge

investment that may be capable of capturing this dynamic explicitly. Numerical modeling and further observations are also necessary to confirm that this mechanism will act similarly on timescales longer than observed here. If so, these results identify a subtle but widespread protective mechanism that will impact the evolution of glacier and ice sheet flow dynamics.

[23] **Acknowledgments.** Thanks to Shad O'Neel for edits and Neil Lareau for advice on temperature downscaling. E. Burgess was funded under the NASA Earth Science Space Fellowship and NASA NNX13AD52A. R. Forster and velocity tracking were funded by NASA grants NNX08AP27G and NNX08AX88G. C. Larsen and E. Burgess were supported by NASA's Operation Ice Bridge grant NASA NNX13AD52A. The Alaska Satellite Facility provided ALOS data.

[24] The Editor thanks two anonymous reviewers for their assistance in evaluating this manuscript.

References

Arendt, A. A., S. B. Luthcke, and R. Hock (2009), Glacier changes in Alaska: Can mass-balance models explain GRACE mascon trends?, *Ann. Glaciol.*, *50*(50), 148–154, doi:10.3189/172756409787769753.

Arendt, A., S. Luthcke, A. Gardner, S. O'Neel, D. Hill, G. Moholdt, and W. Abdalati (2013), Analysis of a GRACE global mascon solution for Gulf of Alaska Glaciers, *J. Glaciol.*, *59*(217), 913–924, doi:10.3189/2013JoG12J197.

Bartholomaus, T. C., R. S. Anderson, and S. P. Anderson (2008), Response of glacier basal motion to transient water storage, *Nat. Geosci.*, *1*(1), 33–37.

Burgess, E. W., R. R. Forster, C. F. Larsen, and M. Braun (2012), Surge dynamics on Bering Glacier, Alaska, in 2008–2011, *The Cryosphere*, *6*(6), 1251–1262, doi:10.5194/tc-6-1251-2012.

Burgess, E. W., R. R. Forster, and C. F. Larsen (2013), Flow velocities of Alaska glaciers, *Nat. Commun.*, *4*, doi:10.1038/ncomms3146.

Cuffey, K. M., and W. S. B. Paterson (2010), *The Physics of Glaciers*, 4th ed., Academic Press, Burlington, Mass.

Harrison, W. D., and A. S. Post (2003), How much do we really know about glacier surging?, *Ann. Glaciol.*, *36*, 1–6.

Hewitt, I. J., C. Schoof, and M. A. Werder (2012), Flotation and free surface flow in a model for subglacial drainage. Part 2: Channel flow, *J. Fluid Mech.*, *702*, 157–187, doi:10.1017/jfm.2012.166.

Hock, R. (2003), Temperature index melt modelling in mountain areas, *J. Hydrol.*, *282*(1–4), 104–115, doi:10.1016/S0022-1694(03)00257-9.

Horel, J., M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciliberti, S. Lazarus, J. Slemmer, D. Zaff, and J. Burks (2002), Mesowest: Cooperative mesonets in the western United States, *Bull. Am. Meteorol. Soc.*, *83*(2), 211–225, doi:10.1175/1520-0477(2002)083<0211:MCMITW>2.3.CO;2.

Huber, P. J., and E. M. Ronchetti (2009), *Robust Statistics*, 2nd ed., Wiley Series in Probability and Statistics, Wiley, Hoboken, N. J.

Iken, A., and R. Bindschadler (1986), Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism, *J. Glaciol.*, *32*(110), 101–119.

Iken, A., and M. Truffer (1997), The relationship between subglacial water pressure and velocity of Findelengletscher, Switzerland, during its advance and retreat, *J. Glaciol.*, *43*(144), 328–338.

Kamb, B. (1987), Glacier surge mechanism based on linked cavity configuration of the basal water conduit system, *J. Geophys. Res.*, *92*(B9), 9083–9100, doi:10.1029/JB092iB09p09083.

Motyka, R. J., S. O'Neel, C. L. Connor, and K. A. Echelmeyer (2003), Twentieth century thinning of Mendenhall Glacier, Alaska, and its relationship to climate, lake calving, and glacier run-off, *Global Planet. Change*, *35*(1), 93–112, doi:10.1016/S0921-8181(02)00138-8.

O'Neel, S., W. T. Pfeffer, R. Krimmel, and M. Meier (2005), Evolving force balance at Columbia Glacier, Alaska, during its rapid retreat, *J. Geophys. Res.*, *110*, F03012, doi:10.1029/2005JF000292.

Ohmura, A. (2001), Physical basis for the temperature-based melt-index method, *J. Appl. Meteorol.*, *40*(*4*), 753–761, doi:10.1175/1520-0450(2001)040<0753:PBFTTB>2.0.CO;2.

Parizek, B. R., and R. B. Alley (2004), Implications of increased Greenland surface melt under global-warming scenarios: Ice-sheet simulations, *Quat. Sci. Rev.,*, *23*(9–10), 1013–1027.

Pelto, M. S., M. M. Miller, G. W. Adema, M. J. Beedle, S. R. McGee, K. F. Sprenke, and M. Lang (2008), The equilibrium flow and mass balance of the Taku Glacier, Alaska 1950–2006, *The Cryosphere*, *2*(2), 147–157, doi:10.5194/tc-2-147-2008.

Schoof, C. (2010), Ice-sheet acceleration driven by melt supply variability, *Nature*, *468*(7325), 803–806, doi:10.1038/nature09618.

Schoof, C., I. J. Hewitt, and M. A. Werder (2012), Flotation and free surface flow in a model for subglacial drainage. Part 1; Distributed drainage, *J. Fluid Mech.*, *702*, 126–156.

Shannon, S. R., et al. (2013), Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise, *Proc. Natl. Acad. Sci. U.S.A.*, *110*(35), 14,156–14,161, doi:10.1073/pnas.1212647110.

Sole, A., P. Nienow, I. Bartholomew, D. Mair, T. Cowton, A. Tedstone, and M. A. King (2013), Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers, *Geophys. Res. Lett.*, *40*, 1–5, doi:10.1002/grl.50764.

Sundal, A. V., A. Shepherd, P. Nienow, E. Hanna, S. Palmer, and P. Huybrechts (2011), Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage, *Nature*, *469*(7331), 521–524, doi:10.1038/nature09740.

Truffer, M., W. D. Harrison, and R. S. March (2005), Correspondence: Record negative glacier balances and low velocities during the 2004 heat wave in Alaska, USA: Implications for the interpretation of observations by Zwally and others in Greenland, *J. Glaciol.*, *51*, 663–664, doi:10.3189/172756505781829016.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*(612), 2961–3012, doi:10.1256/qj.04.176.

Walder, J., and B. Hallet (1979), Geometry of former subglacial water channels and cavities, *J. Glaciol.*, *23*(89), 335–346.

Werder, M. A., I. J. Hewitt, C. G. Schoof, and G. E. Flowers (2013), Modeling channelized and distributed subglacial drainage in two dimensions, *J. Geophys. Res. Earth Surf.*, *118*, 1–19, doi:10.1002/jgrf.20146.